

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. <b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b>					
1. REPORT DATE (DD-MM-YYYY) 13-Sep-2005		2. REPORT TYPE Briefing Charts		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE  An Overview of the Experimental 50-cm Laser Ramjet (X-50LR) Program (Preprint)				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Franklin B. Mead, Jr., C. William Larson, and Sean D Knecht (AFRL/PRSP)				5d. PROJECT NUMBER 4847	
				5e. TASK NUMBER 0159	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  Air Force Research Laboratory (AFMC) AFRL/PRSP 10 E. Saturn Blvd. Edwards AFB CA 93524-7680				8. PERFORMING ORGANIZATION REPORT NUMBER  AFRL-PR-ED-VG-2005-394	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)  Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-70448				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S NUMBER(S) AFRL-PR-ED-VG-2005-394	
12. DISTRIBUTION / AVAILABILITY STATEMENT  Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Presented at the 4 <sup>th</sup> International Symposium on Beamed Energy Propulsion, Nara, Japan, 11-14 Nov 2005.					
14. ABSTRACT In January 2001, the X-50LR program was initiated to scale the Lightcraft concept ultimately to a 50-cm focal diameter, and to launch a 50 cm, fully functional vehicle, into space in either a sounding rocket or suborbital trajectory by the end of FY 2009. The current work involves scaling from a 10-cm aluminum Lightcraft to a composite 25-cm laser ramjet vehicle (X-25LR). An overview and status of this program will be given in terms of the various efforts that support this development. These efforts will include testing at the High Energy Laser System Test Facility (HELSTF), New Mexico; some results of the laser launch system study by Flight Unlimited; the development of silicon carbide materials for X-25LR parabolic reflectors by Trex Enterprises; supporting research by Air Force Office of Scientific Research (AFOSR); the different facets of attitude control in a small business program with Polaris Sensors Technology; continuing development of a launch model at The Pennsylvania State University; and, the development of a thrust measurement technique, and the use of a "mini-thruster" for research with The University of Alabama, Huntsville, in collaboration with the AFRL. This paper will be followed by a number of papers giving additional details of the efforts briefly overviewed in this presentation.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  A	18. NUMBER OF PAGES  25	19a. NAME OF RESPONSIBLE PERSON Dr. Franklin B. Mead, Jr.
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)
Unclassified	Unclassified	Unclassified			(661) 275-5929

# ***An Overview of the Experimental 50-cm Laser Ramjet (X-50LR) Program (Preprint)***

**The 4<sup>th</sup> International Symposium on Beamed Energy Propulsion  
15-18 November 2005  
Nara, Japan**



**Dr. Franklin B. Mead, Jr.,  
Dr. C. William Larson, and  
Mr. Sean D. Knecht  
Propulsion Directorate  
Air Force Research Laboratory  
Edwards Air Force Base, CA**

**This briefing is distribution A: Approved for public release, distribution unlimited**

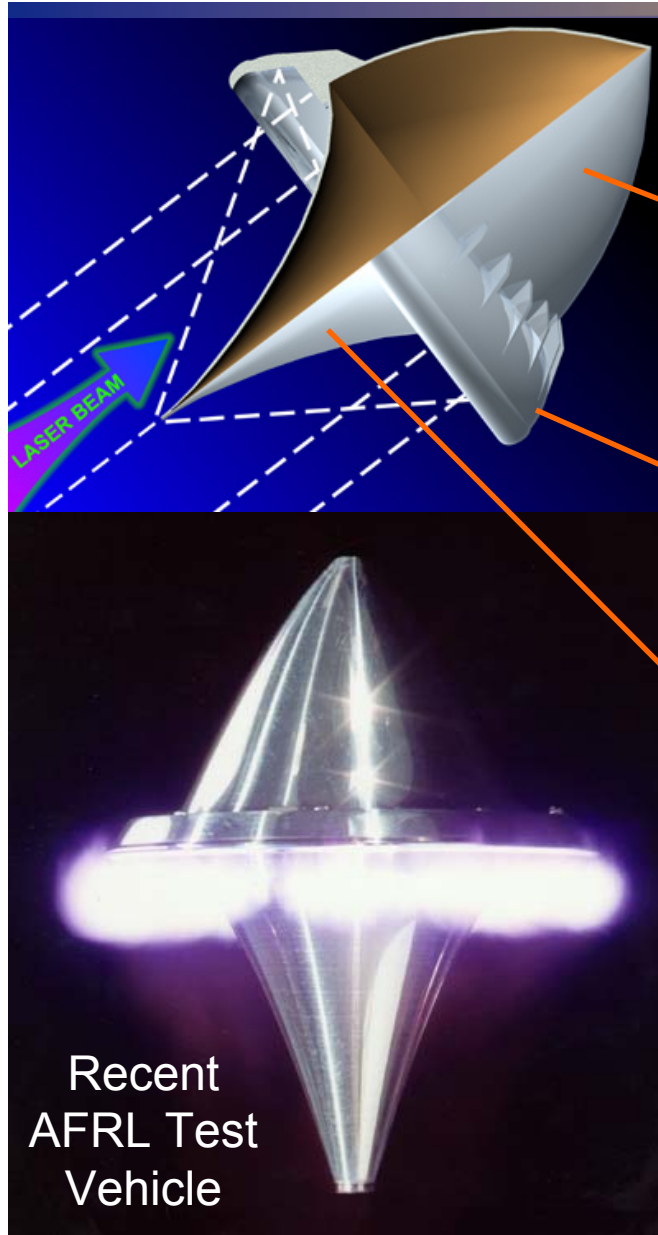


# ***Presentation Outline***

- **The Lightcraft Concept**
- **The Experimental 50-cm Laser Ramjet (X-50LR) Program**
  - **Objectives, Critical Technologies, and Payoffs**
  - **Current Program Collaborations And Technical Contributions**
    - **Testing at HELSTF**
      - **X-25LR**
      - **10-cm Lightcraft**
      - **Mini-thruster research**
    - **AFOSR Programs and Support**
      - **High  $I_{sp}$  Propellants**
    - **Attitude Control (Phase II SBIR)**
      - **Thermal Structural Analysis of Parabolic Plug Nozzle**
      - **Adjustable Pivot Point Pendulum**
    - **Some Launch Code Results**
- **Summary**



# The Lightcraft Concept



- A Lightcraft is a small spacecraft; diameter is  $\leq 1.0$  m, weight is  $\leq 8.0$  kg ( $\leq 2.0$  kg payload)

## **Forebody**

- Aerodynamically contoured surface
- Analogous to rocket payload bay; opens in space to release payload and expose solar cells

## **Shroud**

- Centrally located “belt”
- Analogous to rocket combustion chamber; ejected plasma provides thrust

## **Afterbody**

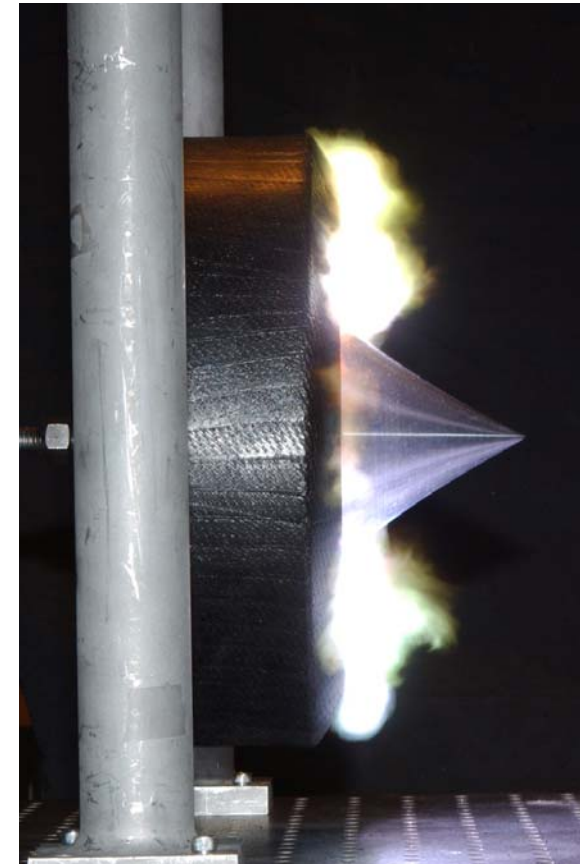
- Analogous to rocket nozzle; parabolic mirror and plug nozzle



# AFRL/PRS Program For Laser Propulsion Development



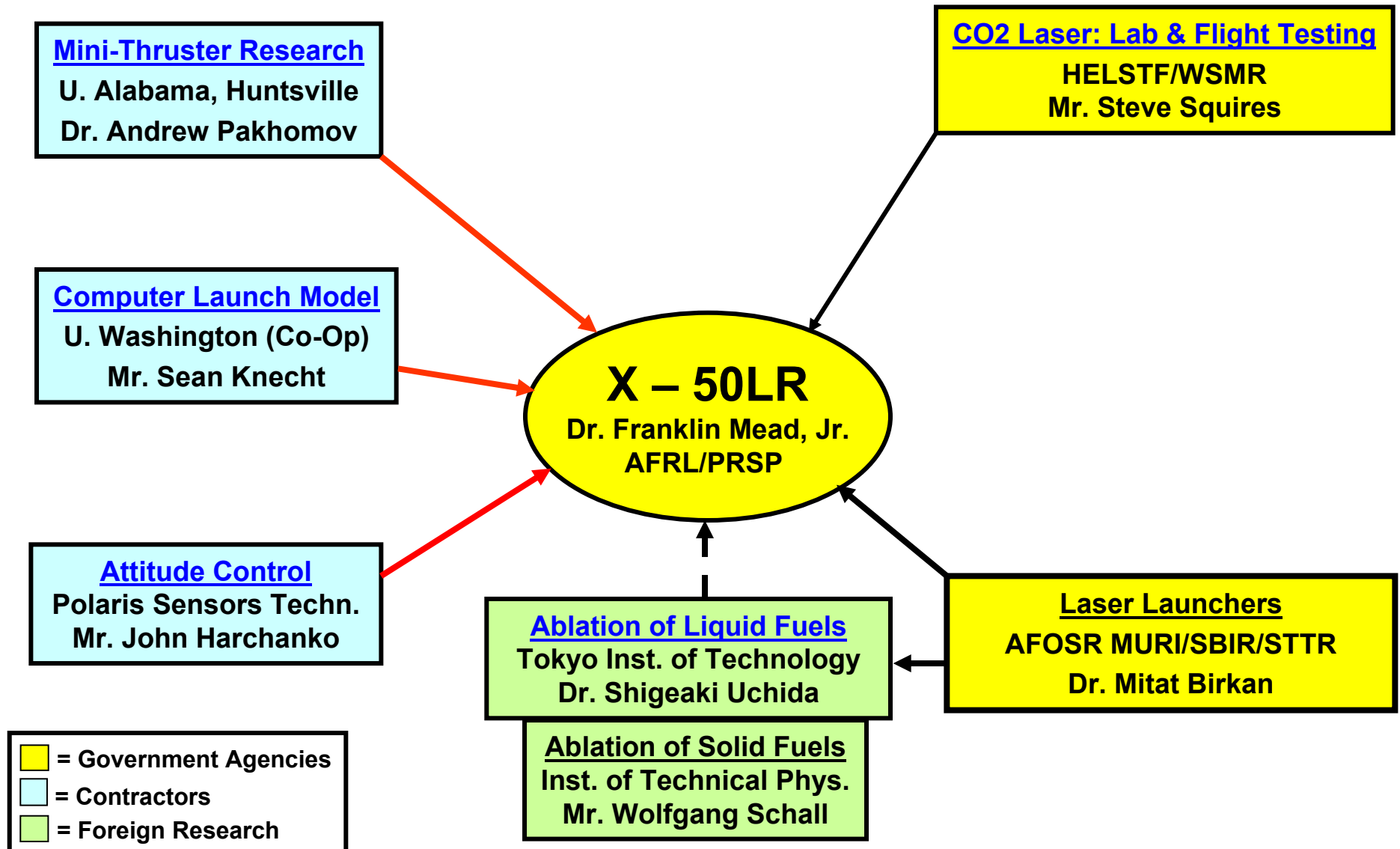
- **Objectives**
  - **Eliminate remaining major technical hurdles for a laser launch vehicle**
    - **Critical Technologies**
      - Airframe & Structure - Materials
      - Ablative energetic propellants
      - Theoretical modeling and flight simulation
      - Electronic Systems
      - Chemical Propulsion
  - **Conduct a high altitude flight demonstration using the technology developed under this program**
    - Using PLVTS CO<sub>2</sub> laser upgraded in power by factor of 2 or 3
- **Payoffs**
  - **Provide a paradigm shift for space access**
    - **Entirely different infrastructure**
      - No huge motorized tractors for moving vehicles
      - No skyscraper gantries
      - No standing army of mechanics & technicians
      - No toxic fuels
      - No significant explosive hazards
      - No large propellant farms
  - **Low cost access to space for nano-satellites**



25 cm Laboratory Model



# Current Program Collaborations







# ***Pulsed Laser Vulnerability Test System (PLVTS)***



## **Original Performance**

- 1,000 joules/pulse
- 10 Hz
- 30  $\mu$ sec pulses

## **Modified Performance**

- 1998
  - 400 joules/pulse
  - 25 Hz
  - 18  $\mu$ sec pulses
- 1999
  - 150 joules/pulse
  - 30 Hz
  - 5  $\mu$ sec pulses



## **Proposed Performance**

- 1,500 joules/pulse
- 20 to 35 Hz
- 25  $\mu$ s pulses

*The PLVTS has powered the AFRL laser propulsion test and evaluation program*



# ***Team December 2004***

## ***Pulsed Laser Vulnerability Test System***



Frank Mead, Bill Larson, Sean Knecht, AFRL/PRSP  
Jim Shryne, RSI (Photographer)  
John Harchanko, POLARIS TECHNOLOGIES  
Steve Squires, Chris Beairsto, Mike Thurston, &  
Jay Spray, WSMR/HELSTF/PLVTS







# ***Mettler Balance or Digital Balance***



**Measure mass to  $\pm 0.3$  mg**



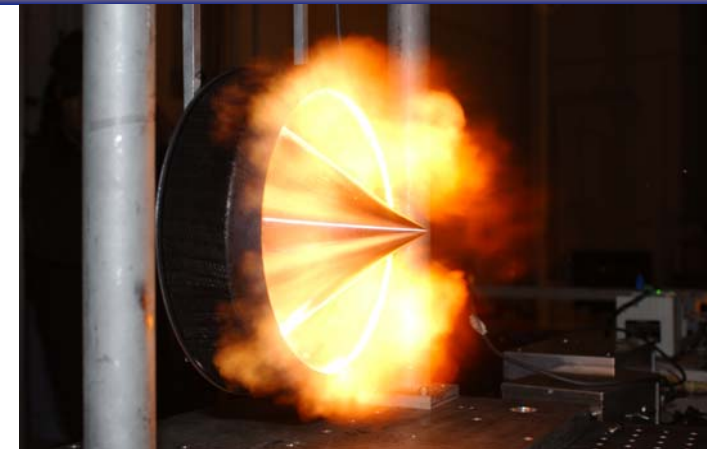


# Laboratory Tests at HELSTF



- **X-25LR Bench Model**

- Fabricated by COI Ceramics
  - Amorphous SiNC Matrix
  - Reinforced with Nicalon fiber
  - Recommended up to 1473° K
- Tested With Delrin®
  - COI Nicalon parabolas gave poor performance
    - Fibers coated with Cu yielded poor, inaccurate mirror quality
  - Required Al parabola with mirror finish
    - Performance Excellent



X-25LR Test with Black Delrin®

- **Shadowgraph Tests in Air**

- 10-cm Aluminum Lightcraft Laboratory Model
- 18  $\mu$ s and 300 J
- Exit plane traverse = 10  $\mu$ s



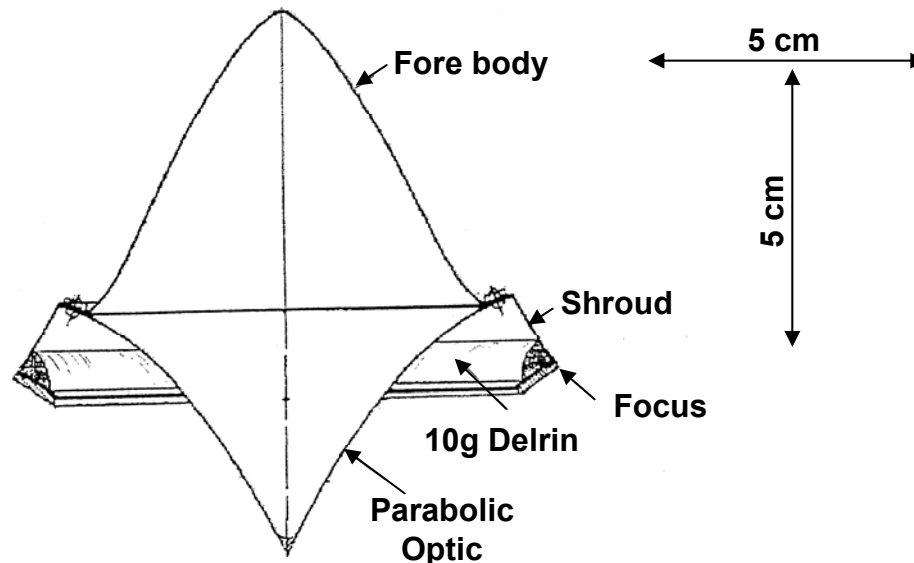
10-cm Lightcraft Shadowgraph Test



# Lightcraft and Mini-Nozzle Standard



## 200-3/4 Lightcraft (10-cm)



$\epsilon$  (ideal plug nozzle) = 14

$M = 40\text{g}$

Delrin surface area  $\sim 25\text{ cm}^2$

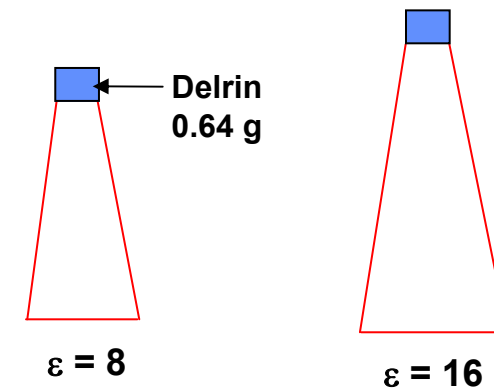
$350\text{ J}/25\text{ cm}^2/18\text{ }\mu\text{s} = 0.8\text{ MW}/\text{cm}^2$

$C_m = 450\text{ N}/\text{MW}$ ,  $E_L/m = 5.1\text{ MJ}/\text{kg}$

$V_e = 2270\text{ m/s}$ , efficiency = 0.51

$T/W = C_m \cdot P/mg = 11$  at  $P=10\text{ kW}$

## Mini-Thruster 26° divergence angle



$\epsilon = 8$

$M = 7.8\text{ g}$

Delrin surface area  $\sim 0.71\text{ cm}^2$

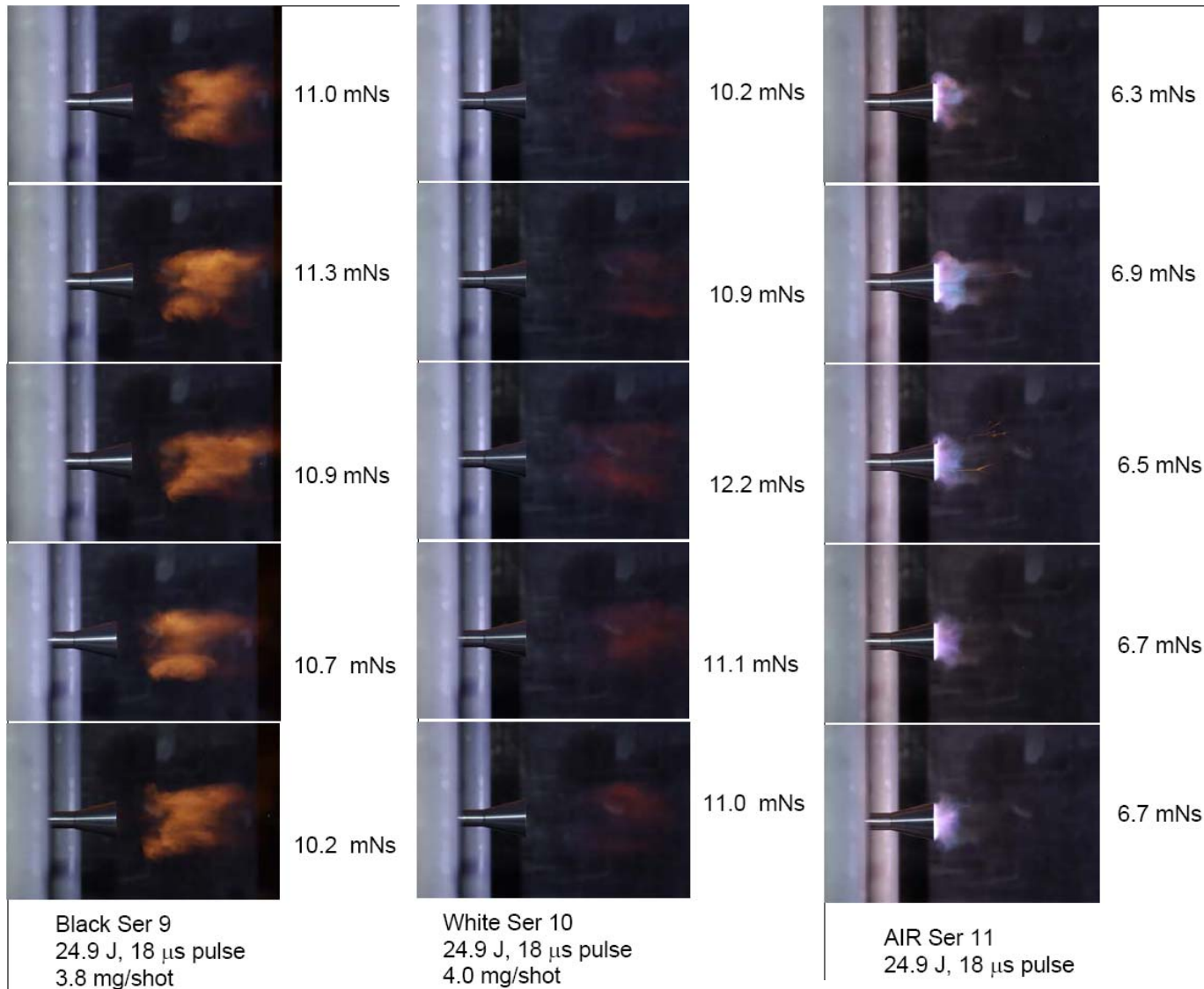
$25\text{ J}/0.71\text{ cm}^2/18\text{ }\mu\text{s} = 2.0\text{ MW}/\text{cm}^2$

$C_m = 442\text{ N}/\text{MW}$ ,  $E_L/m = 6.3\text{ MJ}/\text{kg}$

$V_e = 2795$ , efficiency = 0.62



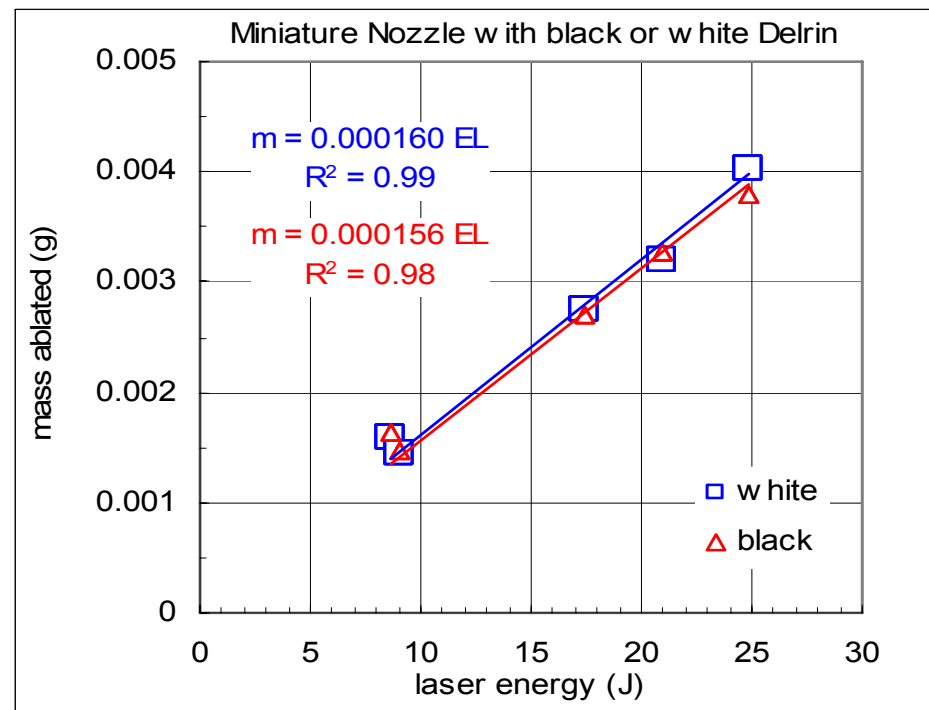
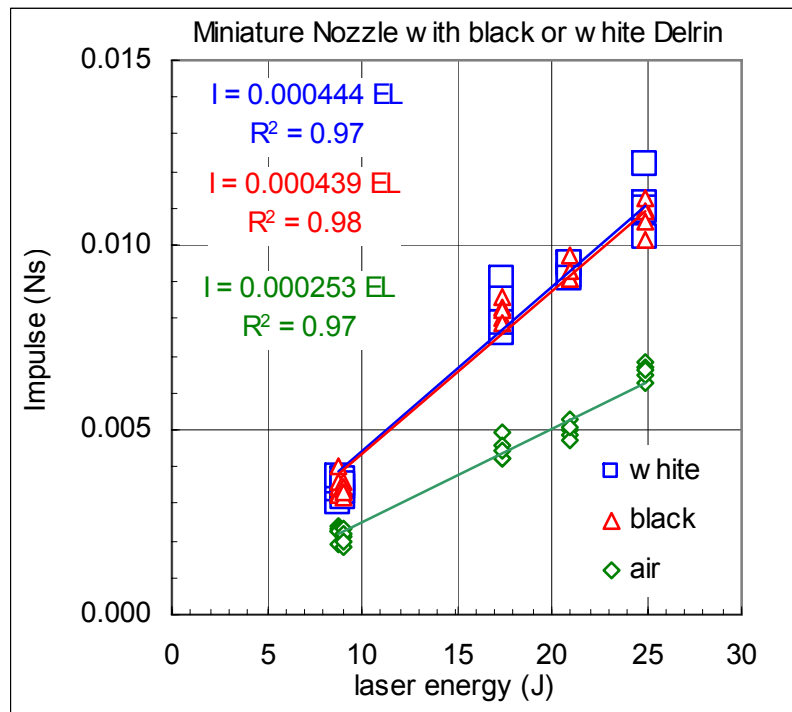
# Mini-Thruster 25 J, 18 $\mu$ s, 0.71 cm<sup>2</sup>







# $I, m, E_L$ for Mini-Thruster



$$I/E_L = 444 \text{ Ns/MJ}$$

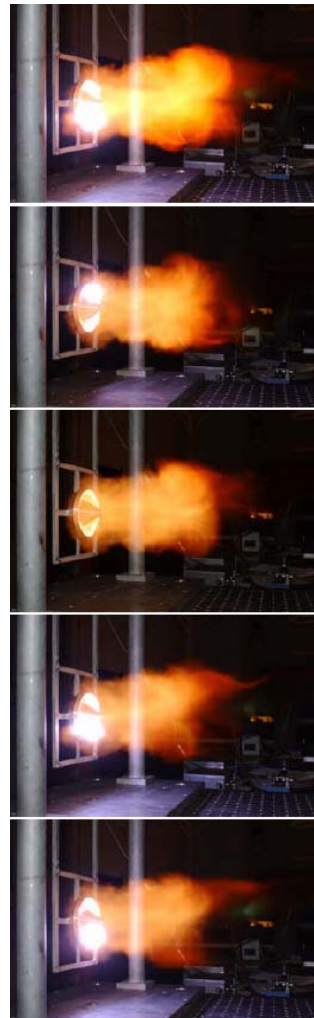
$$m/E_L = 0.160 \text{ mg/J}$$

$$V_e = (I/E_L)/(m/E_L) = 2775 \text{ m/s}$$

$$\text{Efficiency} = \frac{1}{2}(I/E_L)^2/(m/E_L) = 0.616 = \alpha\beta\Phi$$



# 10 cm Light Craft 322 J, 18 $\mu$ s



139.2 mNs

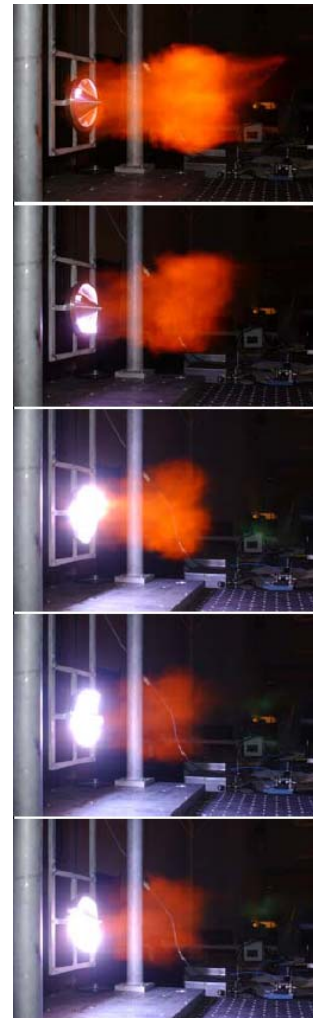
144.8 mNs

153.9 mNs

146.7 mNs

150.2 mNs

Black Ser 7  
322 J  
59.8 mg/shot



154.1mNs

151.8 mNs

133.0 mNs

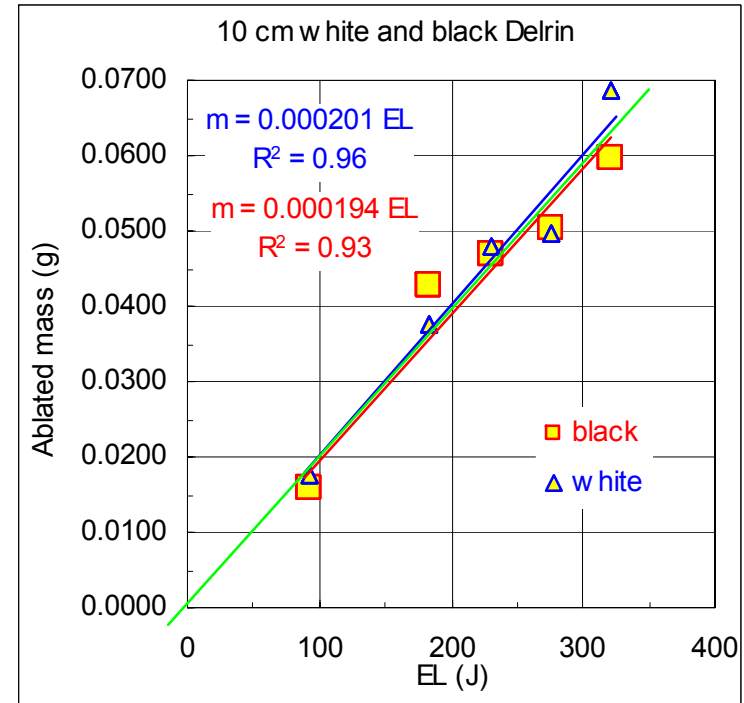
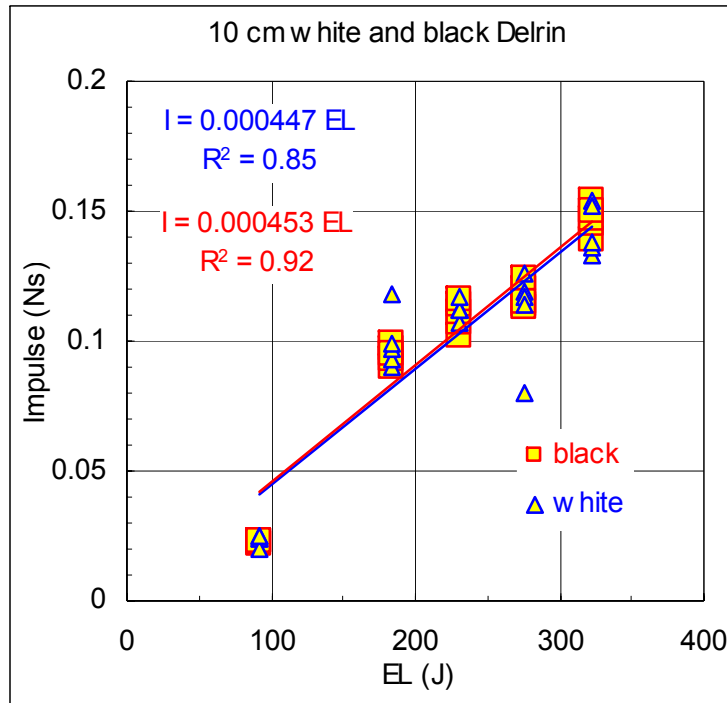
136.1 mNs

137.8 mNs

White Ser 6  
322 J  
68.7 mg/shot



## $I, m, E_L$ for Lightcraft 200-3/4 (10-cm)



$$I/E_L = 447 \text{ Ns/MJ}$$

$$m/E_L = 0.201 \text{ mg/J}$$

$$V_e = (I/E_L)/(m/E_L) = 2224 \text{ m/s}$$

$$\text{Efficiency} = \frac{1}{2}(I/E_L)^2/(m/E_L) = 0.497 = \alpha\beta\Phi$$



## ***Conclusions/Work in Progress***



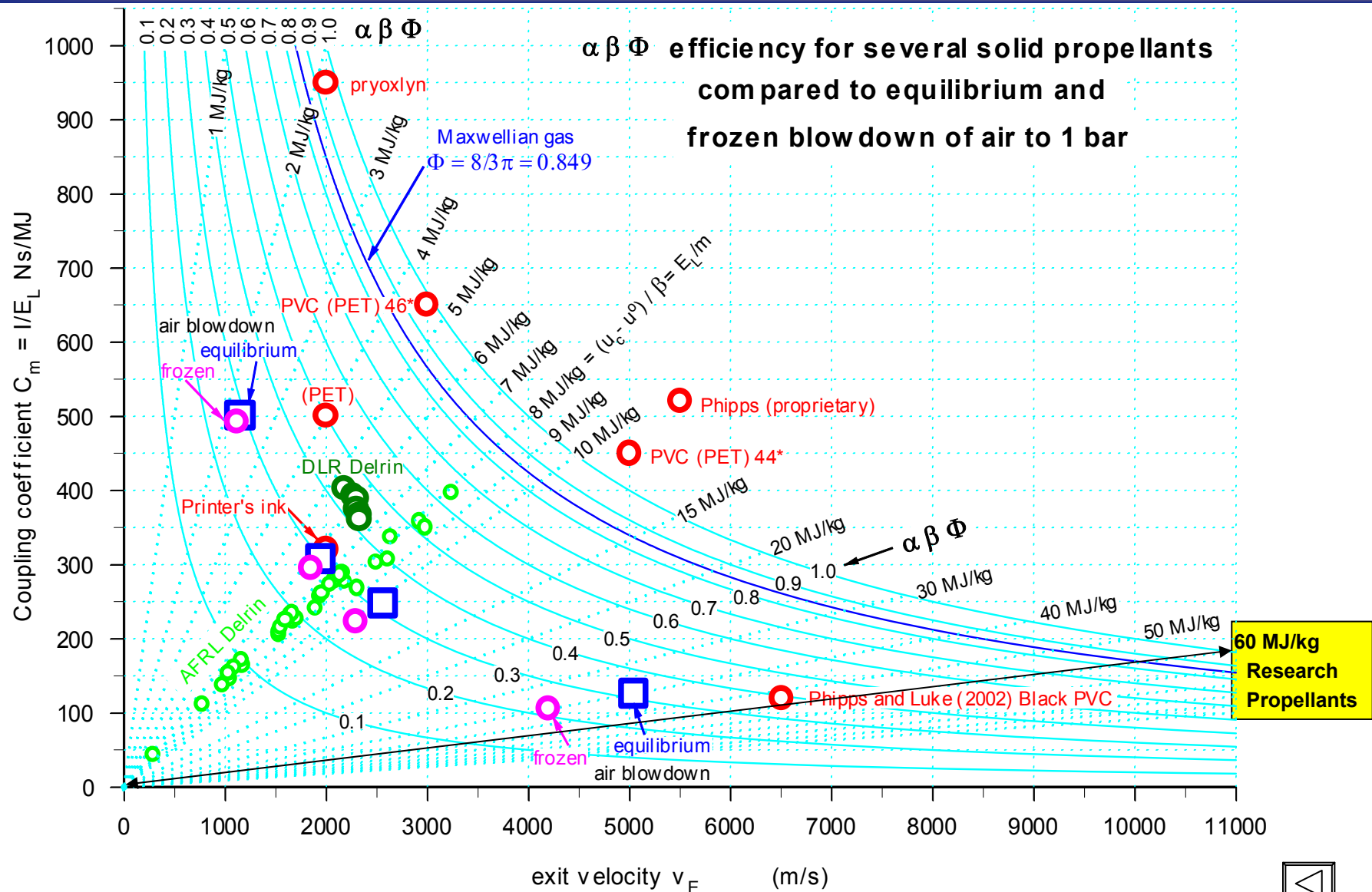
- $C_m = 450$  N/MW for Lightcraft with Delrin<sup>®</sup> (350 J, 18  $\mu$ s)
- $C_m = 442$  N/MW for mini-thruster with Delrin<sup>®</sup> (25 J, 18  $\mu$ s)
- 51 % efficiency for  $E_L$  to jet KE for Lightcraft
- 62 % efficiency for  $E_L$  to jet KE for mini-thruster
- Future experiments
  - Vary pulse width, 5 and 30  $\mu$ s, expansion ratio,  $\varepsilon = 4, 16, \dots$
  - Increase  $E_L$  up to  $\sim 100$  J/pulse in mini-thruster
  - Measure time resolved thrust with piezoelectric sensor
  - Develop chemically enhanced ablative propellants
- Future calculations with chemical equilibrium applications code
  - Factor pressure thrust into analysis
  - Analyze chemically energetic propellants\*







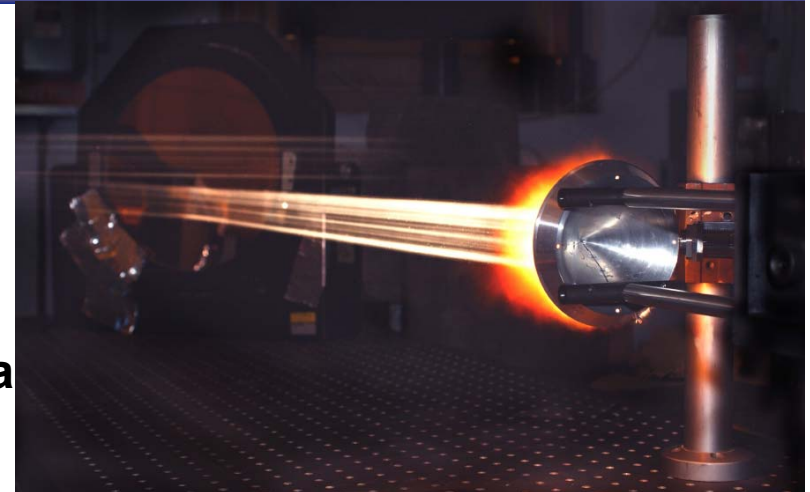
# Performance Map of Known Laser Propellants





# ***Thermal Structural Analysis*** ***(Laser Lightcraft Thin-Walled Aluminum Plug Nozzle)***

- **Performed by SYColman**
  - **Directed by Polaris Sensor Technologies**
    - **Under SBIR Phase II contract for attitude control**
- **Desire to predict deformed shape of parabola as a function of time and input power**
  - **Based on initial geometry and varying temperature**
- **Results from model**
  - **Maximum displacement increases linearly with temperature**
  - **Significant optical degradation and distortion of reflected beam with predicted beam surface deformations**
  - **COI Nicalon material showed little or no resultant deformation  $\leq 1,000^{\circ}$  F**



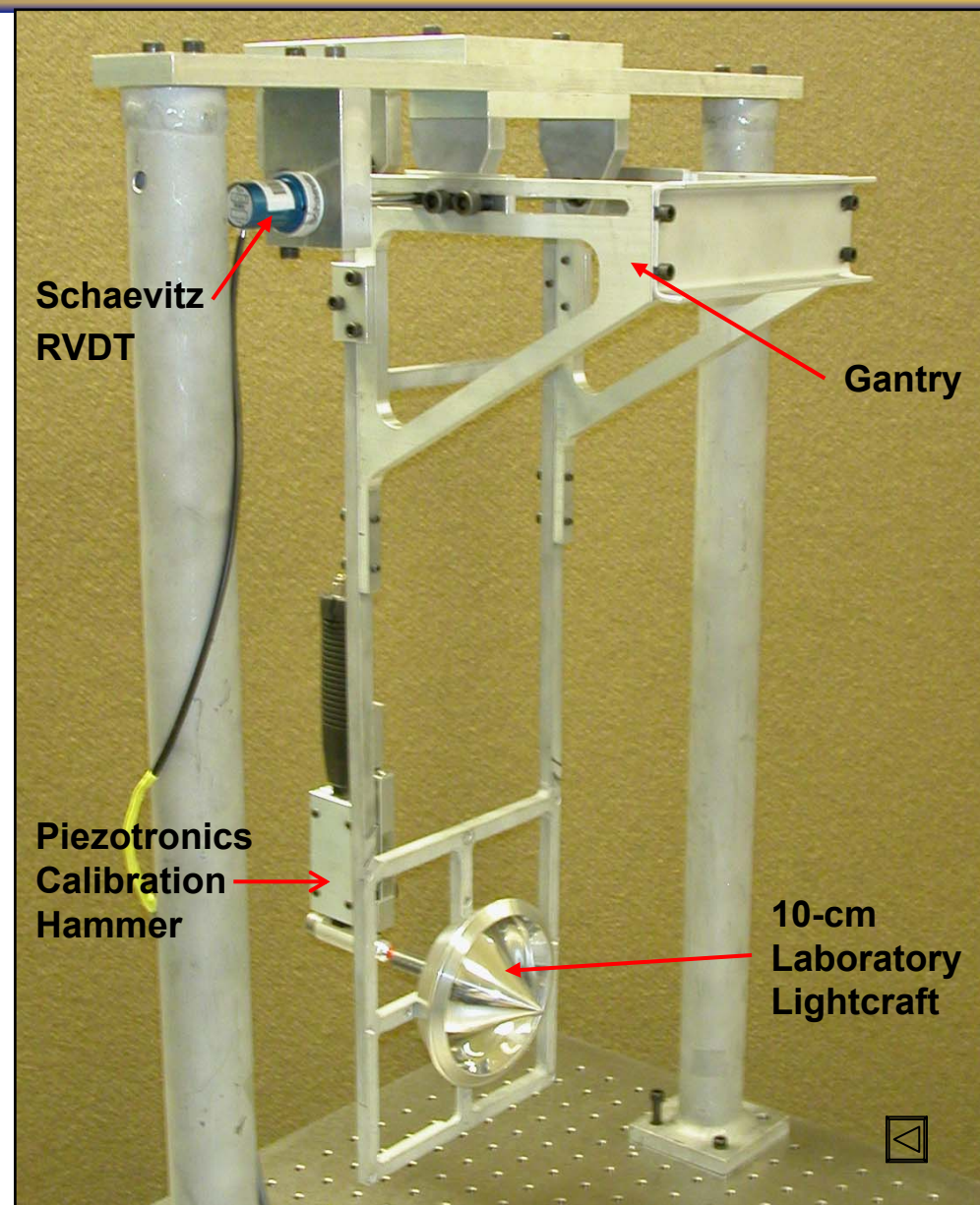
**Full Power, Multi-Pulse Laser Heating of Flight-weight Lightcraft Parabola with Shroud Attached**



# *Impulse Pendulum with Adjustable Pivot Point*



- **Improved technique**
  - Pendulum is brought into balance by adjusting its pivot-point
    - Coincide with Lightcraft/pendulum's combined center of gravity
  - More sensitive than standard pendulum
  - Developed for measuring side/restoring forces
  - Gantry size determines range of test articles that can be handled\*







# ***X-25LR Space Launch Simulation***



- **Pulsed CO<sub>2</sub> laser**
  - 1 MW
  - 1,000 joules/pulse
  - 30 Hz
  - 25  $\mu$ s pulses
- **Vehicle parameters for simulations**
  - 25 cm diameter,
  - Dry mass (structure) = 0.21 kg
  - Payload = 0.21 kg
  - Propellant (mass fraction =  $\frac{1}{2}$ ) = 0.42 kg
  - Total mass = 0.84 kg (1.85 lbs)

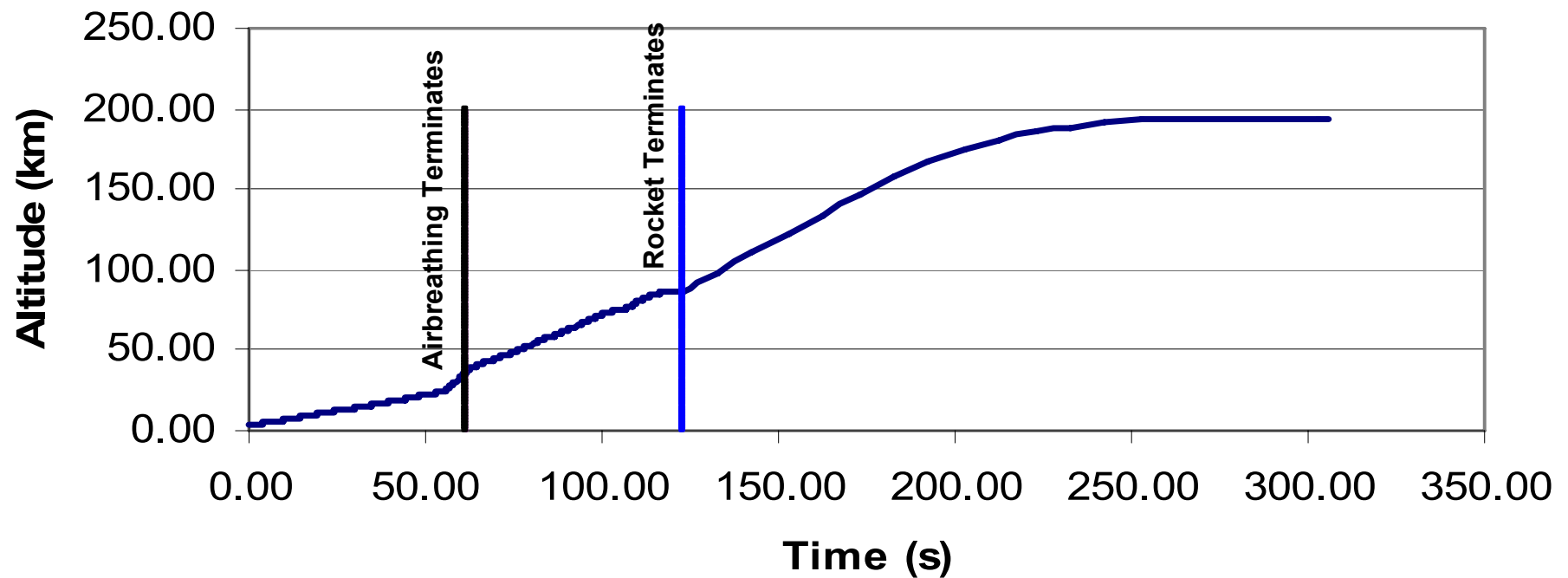




## *Results: 1 MW 10.6 $\mu\text{m}$ Laser*



**Altitude vs. Time of Flight**

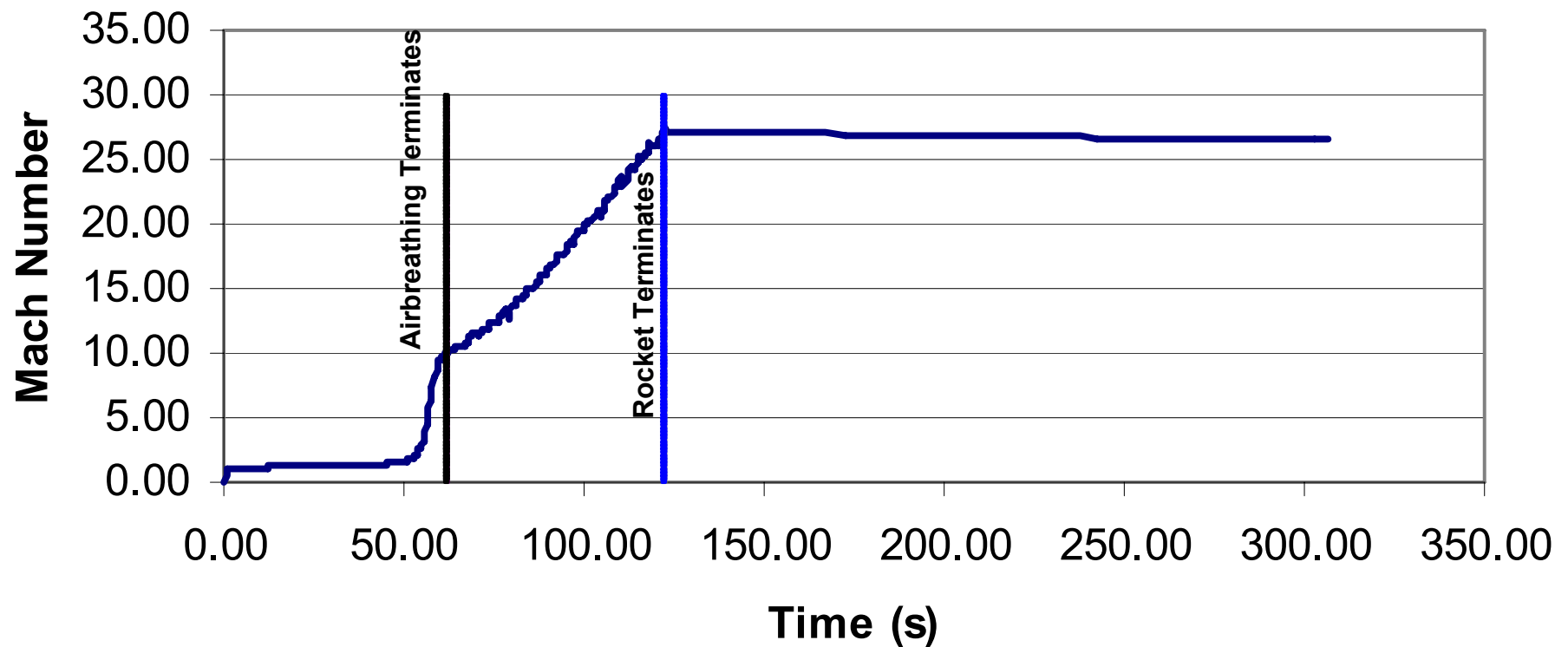




# Results: 1 MW 10.6 $\mu\text{m}$ Laser



## Mach Number vs. Time of Flight

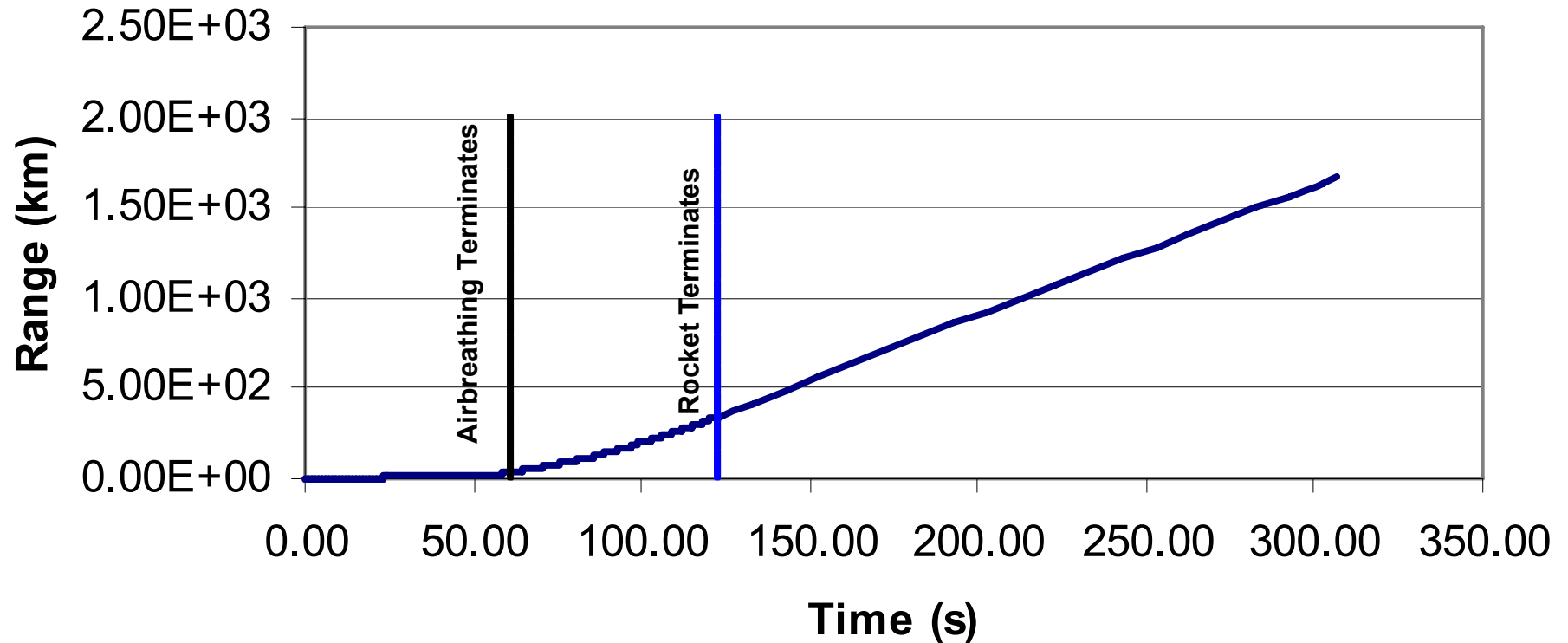




## Results: 1 MW 10.6 $\mu\text{m}$ Laser



### Range from Laser vs. Time of Flight





# X-50LR Program Summary



- AFRL laser propulsion ready for advanced development (6.3) with a quarter scale vehicle
  - Composite, airbreathing, 25-cm vehicle needs additional development
  - High altitude flights are possible using active ACS on a 25-cm laser propelled vehicle
- Critical technologies required to be ready for engineering development (6.4)
  - *Airframe & Structure – Materials*
  - *Ablative energetic propellants*
  - *Theoretical modeling and flight simulation*
  - *Guidance, Control, Power, & Sensors*
  - *Chemical Propulsion*
- Operational status could be reached within 3 to 4 years
  - A MW class laser will be required
  - The major technologies required for laser propulsion will need to be demonstrated under an advanced development program
- A rather modest investment to achieve a means for a new, unique, low-cost access to space



***Laser Propulsion technology has the potential to make low-cost access to space a reality in the near future***





# The End